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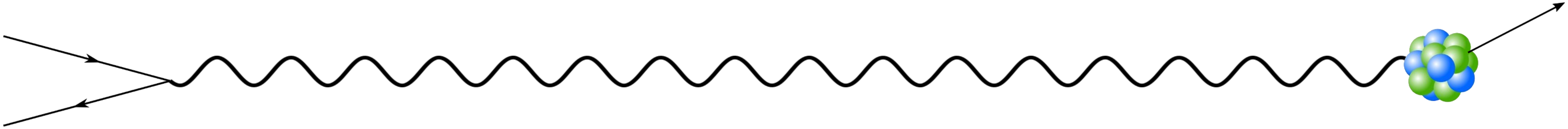
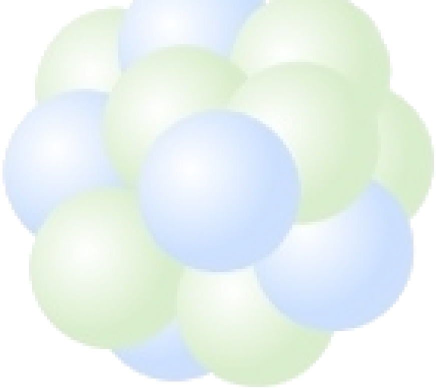
The CONUS Reactor Neutrino Experiment

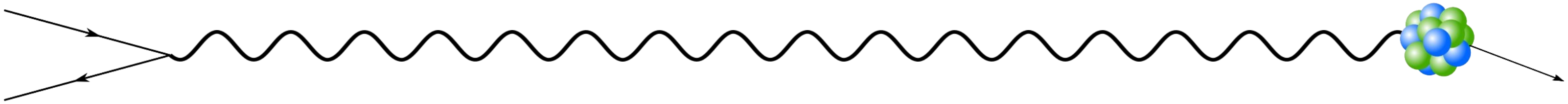


Janine Hempfling (on behalf of the CONUS Collaboration)
Max-Planck-Institut für Kernphysik, Heidelberg

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 43rd Course
20.09.2022



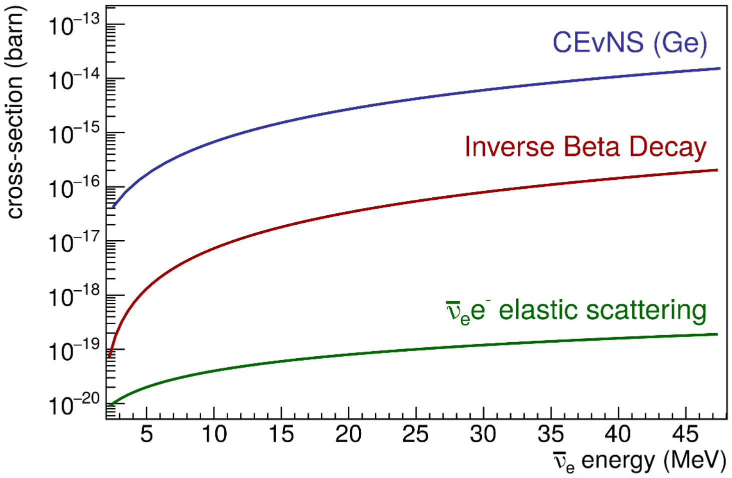
Coherent Elastic Neutrino Nucleus Scattering



Plots by A. Bonhomme

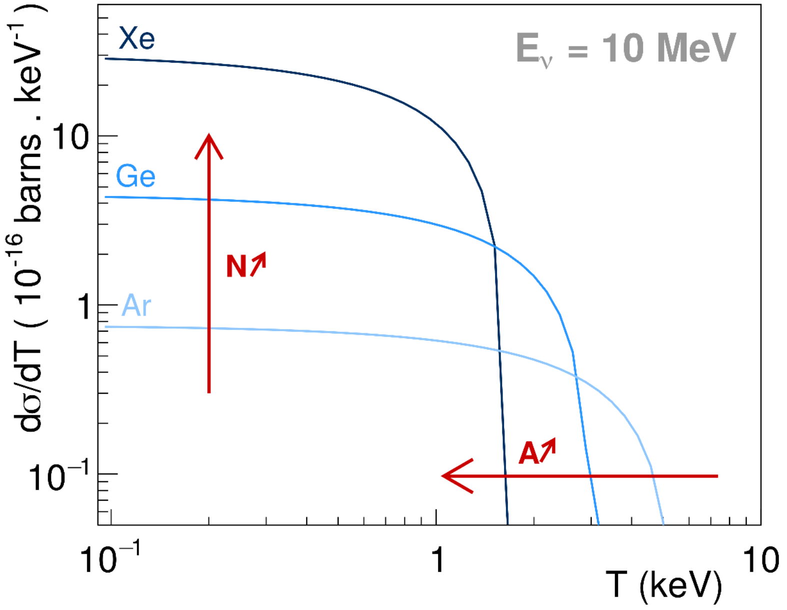
- Coherent interaction of low energy neutrinos with nuclei

$$\frac{d\sigma(E_\nu,T)}{dT} \simeq \frac{G_F^2}{4\pi} \underbrace{[N-(1-4\sin^2(\theta_W))Z]^2}_{\approx N^2} \underbrace{F^2(q^2)}_{\to 1} M \underbrace{\left(1-\frac{MT}{2E_\nu^2}\right)}_{kinematics}$$

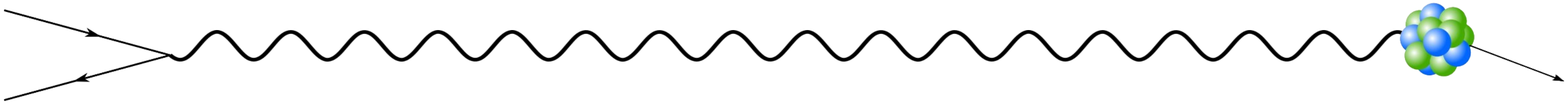


- At low momentum transfer: interaction with entire nucleus
  ➡ cross-section enhancement

- At full coherency: $\sigma \propto N^2$
  for $E_\nu \leq 30$ MeV



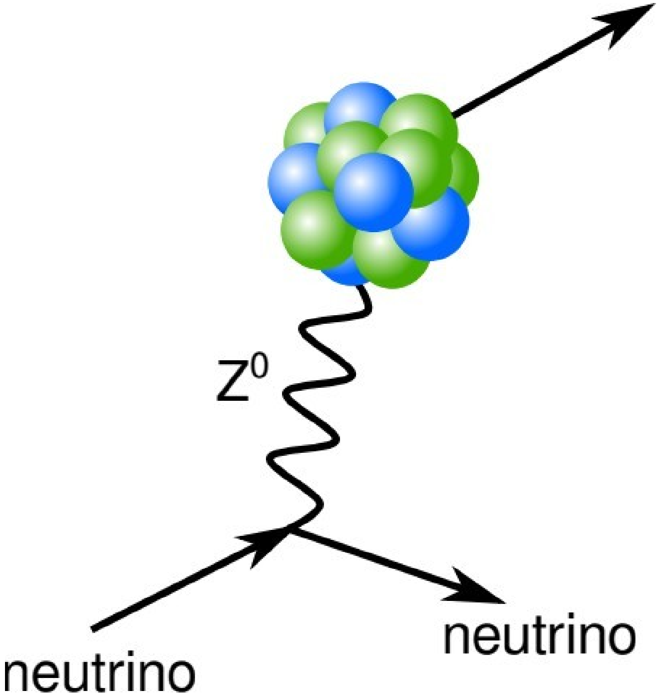
Coherent Elastic Neutrino Nucleus Scattering



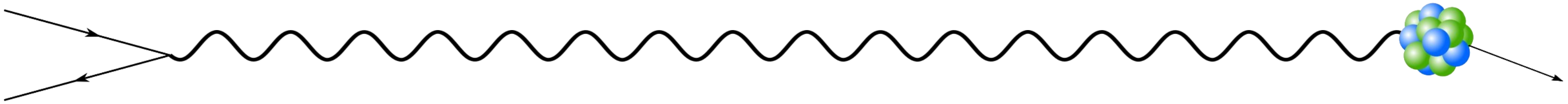
- Only low-energy nuclear recoil observable
  ➡ very low energy threshold, low background and intense ν-flux required

- 1974: CEνNS theoretically described by D. Freedman

- 2017: observed by COHERENT at π-DAR source with CsI[Na] (and Ar in 2021)



Coherent Elastic Neutrino Nucleus Scattering

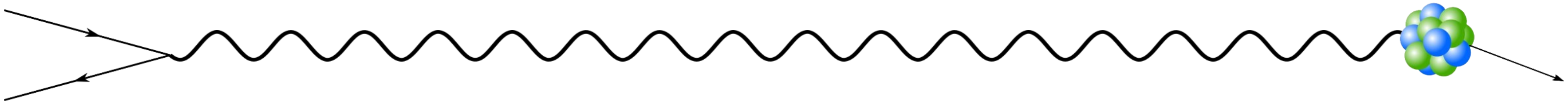


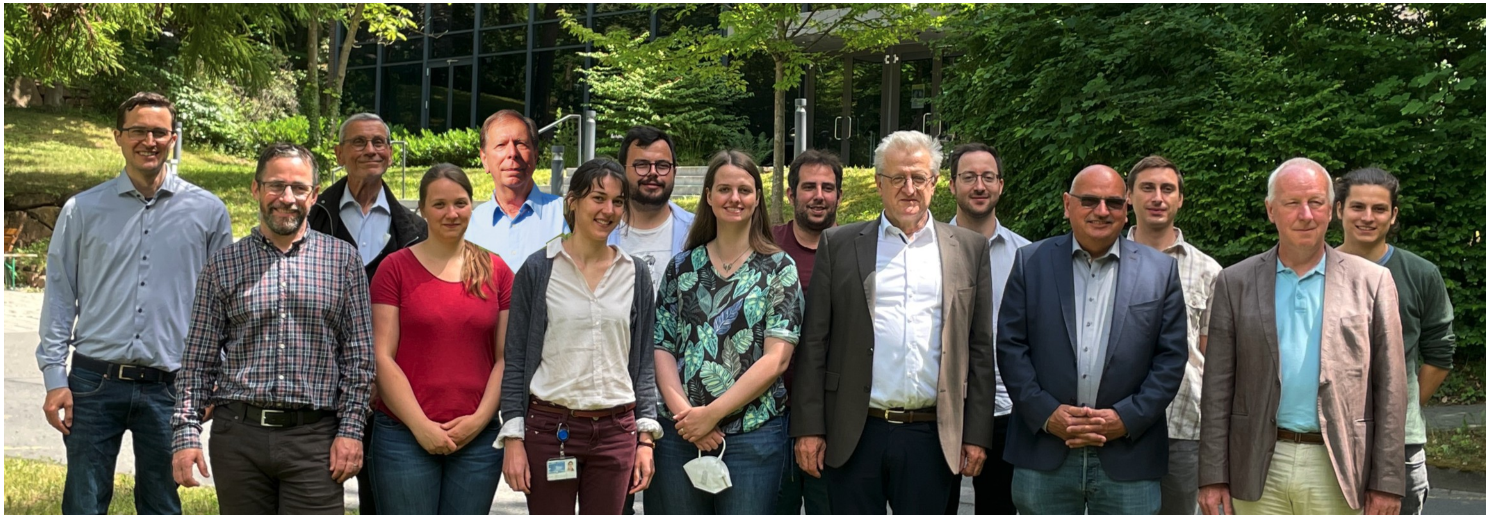
- Detecting CEνNS: How & Why?
  ➡ 2 artificial neutrino sources:

Reactor	Accelerator
ν from fission products	ν from π-DAR
only $\bar{\nu}_e$	different flavors: ν_e, ν_μ, $\bar{\nu}_\mu$
ν energies of < 10 MeV	ν energies of ~20-50 MeV

- Physics potentials:
  - Standard Model measurements (e.g. Weinberg angle)
  - Beyond Standard Model searches
  - Nuclear structure
  - reactor investigations

The CONUS Experiment





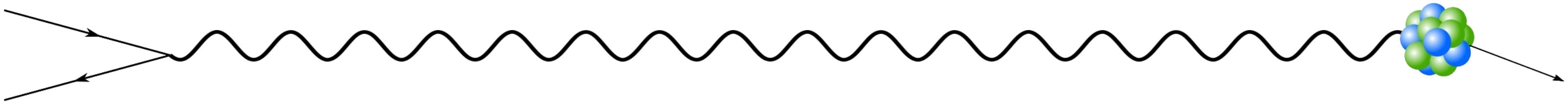
- **<u>The CONUS Collaboration:</u>**

  N. Ackermann, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, J. Henrichs, G. Heusser, M. Lindner, W. Maneschg, T. Rink, E. Sanchez Garcia, J. Stauber, H. Strecker

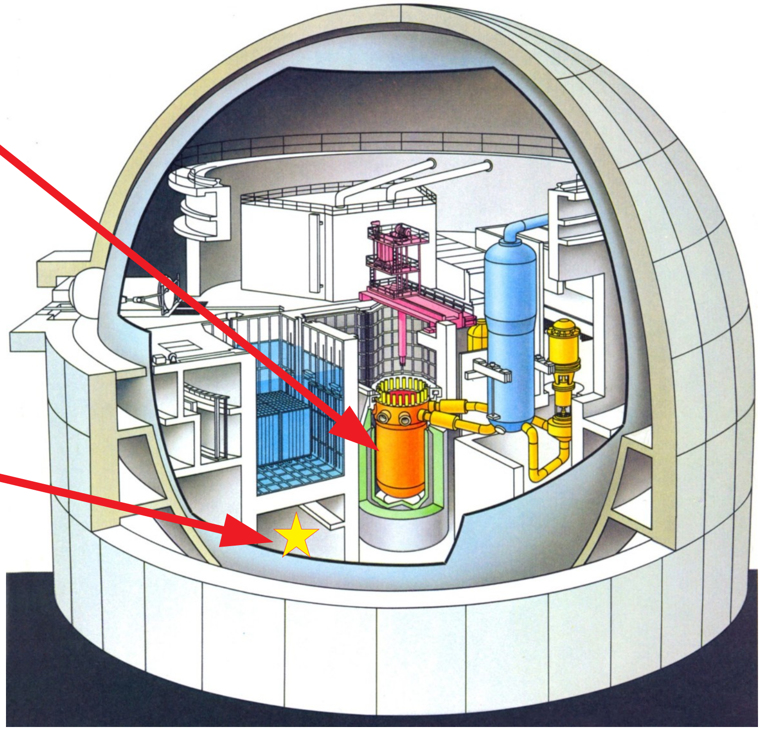
  - Max Planck Institut für Kernphysik (MPIK), Heidelberg

  K. Fülber, R. Wink
  - Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf

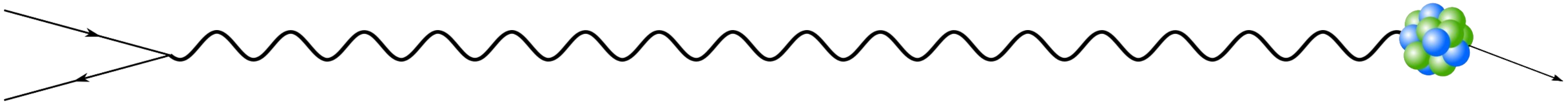
The CONUS Experiment – Experimental Site



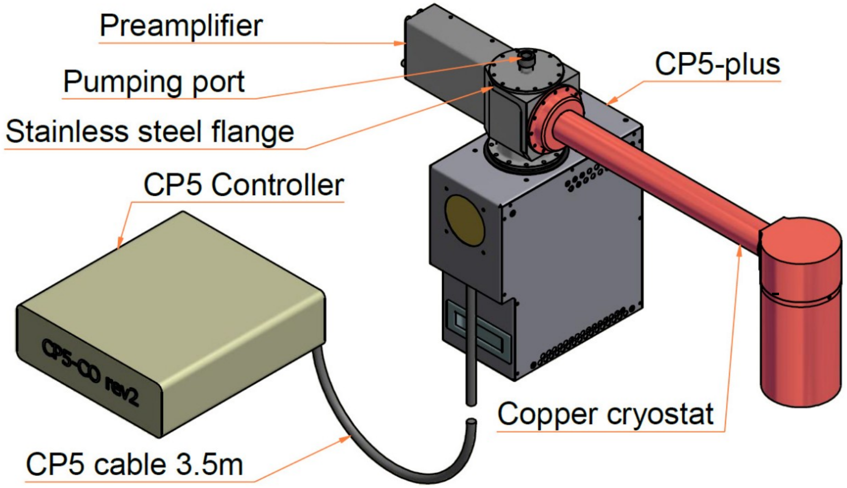
- At the nuclear power plant in Brokdorf (KBR) in Germany
- Reactor core:
  - thermal power $3.9\ \mathrm{GW_{th}}$
- High duty cycle (~1 month/yr off)
- 24 m w.e. overburden (angle-dependent)
- CONUS at 17 m distance to core
  - neutrino flux $2\cdot10^{13}\,\overline{\nu}_e\ \mathrm{s^{-1}\ cm^{-2}}$
- Power plant switched off since beginning of 2022

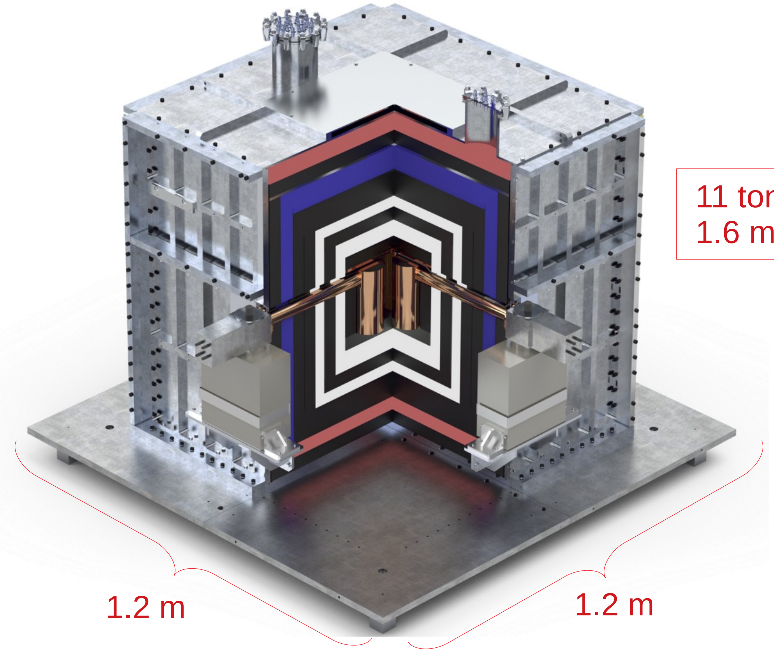


The CONUS Experiment – Experimental Setup



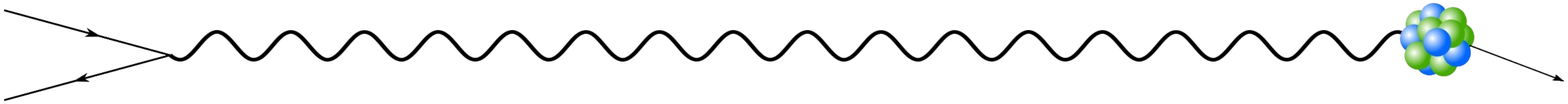
- 4 p-type point contact HPGe detectors
  - 1kg each
  - very low background components
  - electrical cryocooler
  - pulser resolution (FWHM) < 80 eV$_{ee}$
  - energy threshold ≤ 300 eV$_{ee}$
- Active + passive shielding
  - lead with low ^{210}Pb content
  - borated PE, pure PE
  - active µ-veto (plastic scintillator)
- Monitoring of environmental parameters





Eur. Phys. J. C 81, 267 (2021)

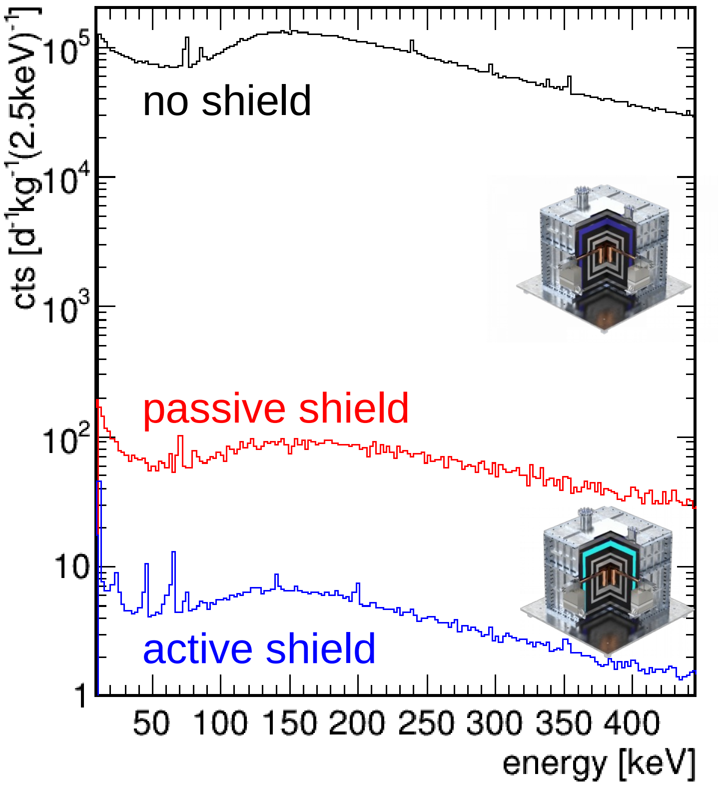
The CONUS Experiment – Background Suppression

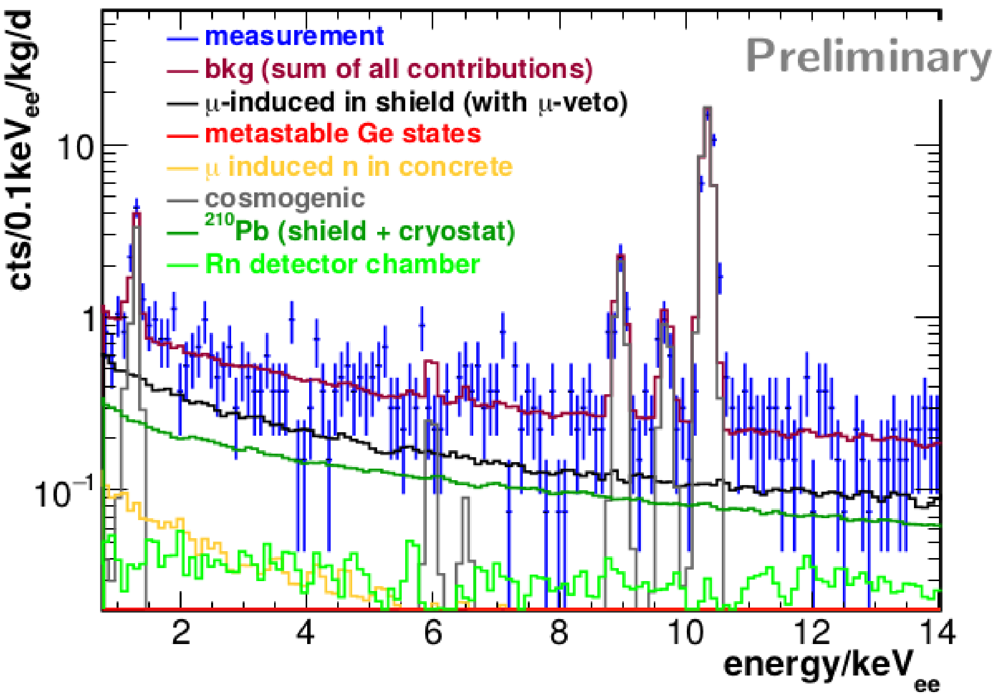


- Suppression of external natural radioactivity and cosmogenic background by a factor of 10^4
- Residual background fully described by MC simulations

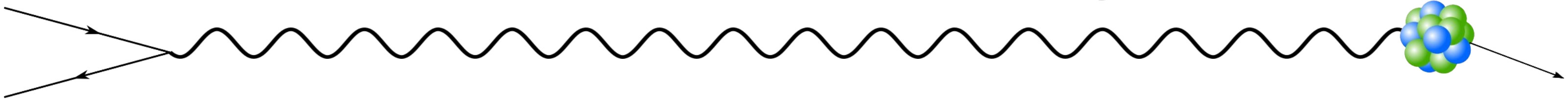
stable background level in [0.5 − 1] $\mathrm{keV_{ee}}$:
10 counts/kg/d/$\mathrm{keV_{ee}}$

Eur. Phys. J. C 79, 699 (2019)
arXiv: 2112.09585 (2021)





Ionization Quenching Factor



Eur. Phys. J. C 82, 815 (2022)

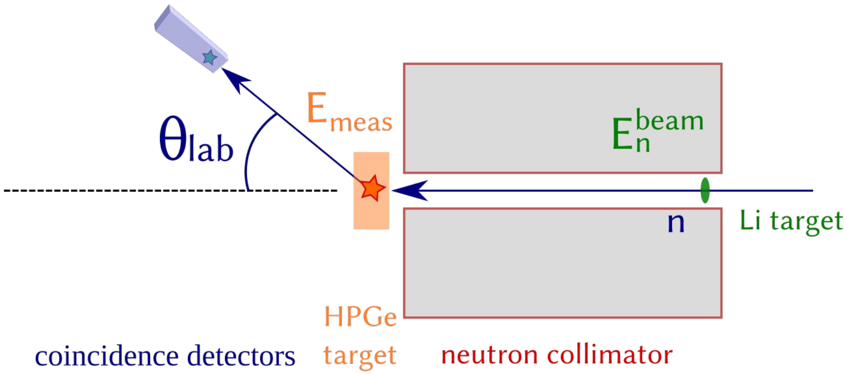
- Ionization quenching factor (IQF)

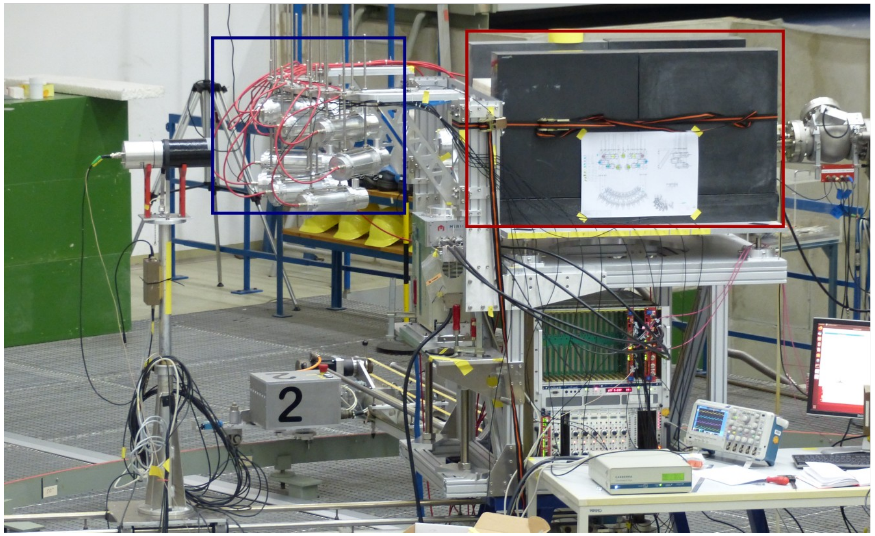
$$IQF = \frac{E_{ionization}}{E_{nuclear\ recoil}}$$

- Extensively measured from 10-100keV, data lacking in keV range → Conus ROI

Measurement of IQF in Ge:

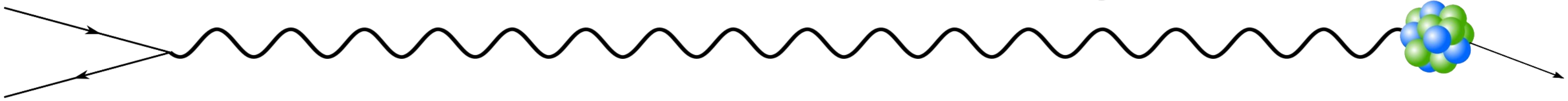
- direct, model-independent using neutrons
- scientific cooperation with PTB:
  - pulsed proton beam
  - mono-energetic neutrons via Li(p,n) reaction
- Experimental setup:
  - neutron collimator
  - thin HPGe target
  - liquid scintillator (LS) array





Images by A. Bonhomme

Ionization Quenching Factor



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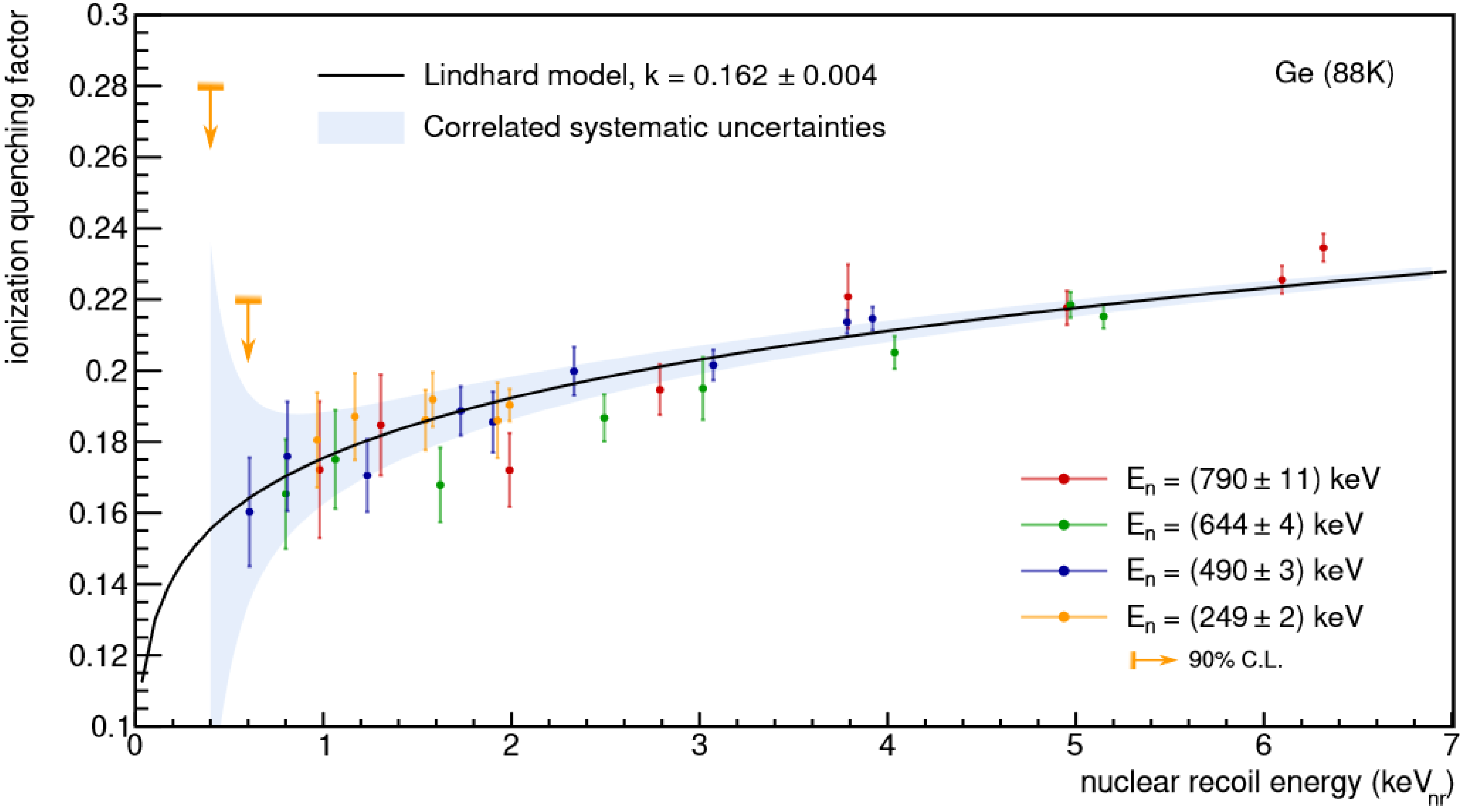
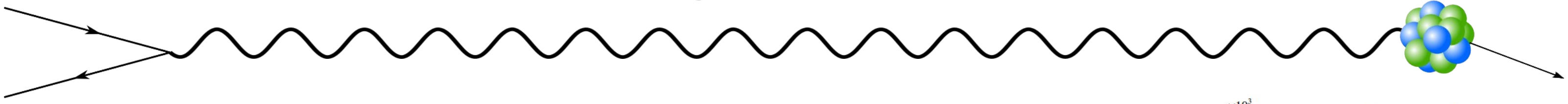
- Model-independent analysis of data (~16h beam exposure)
- All systematic uncertainties included

➡ Data compatible with Lindhard model: $k = 0.162 \pm 0.004\,(stat + syst)$



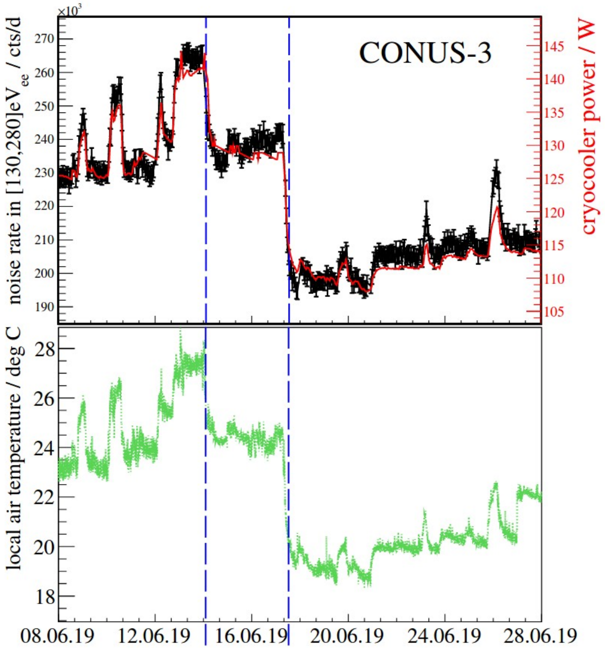
CEνNS Analysis - Data Selection & Noise Cuts

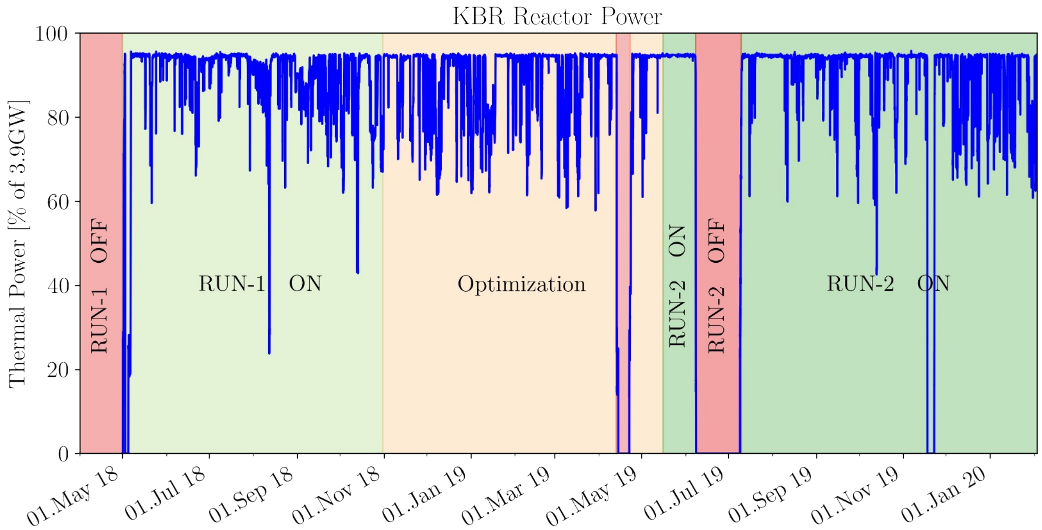


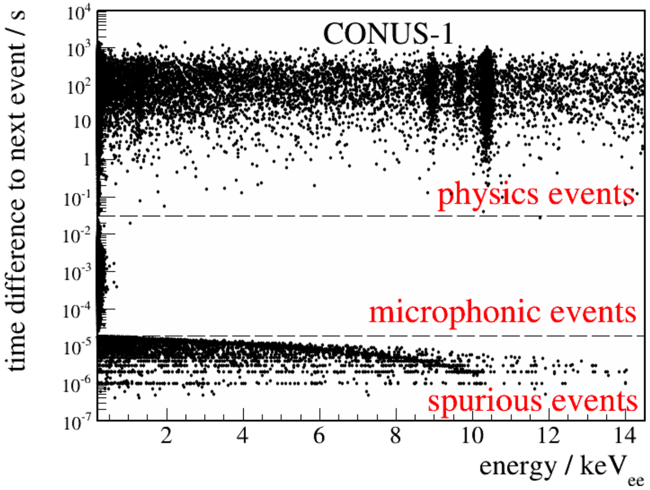
- Noise-temperature correlation cut
- Reject microphonic and spurious events with time-difference distribution cut

➡ Run-1+2 exposure after all cuts:
  - 248.7 kg d (reactor-on)
  - 58.8 kg d (reactor-off)

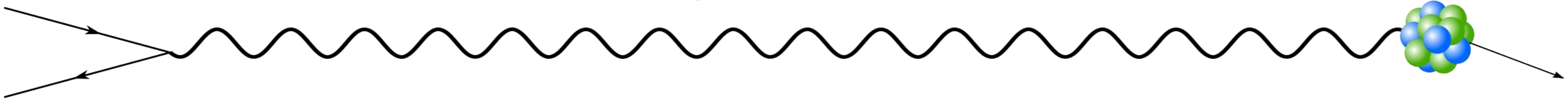
Phys. Rev. Lett. 126, 041804 (2021)



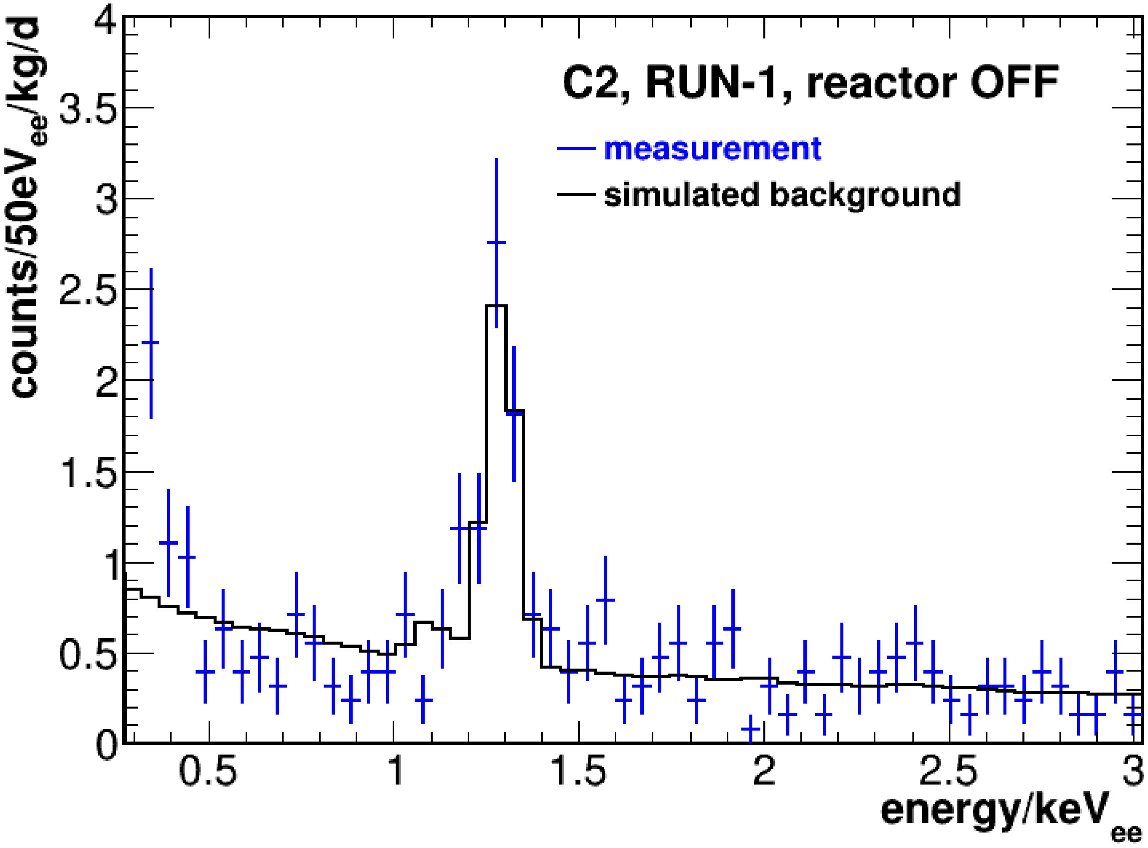




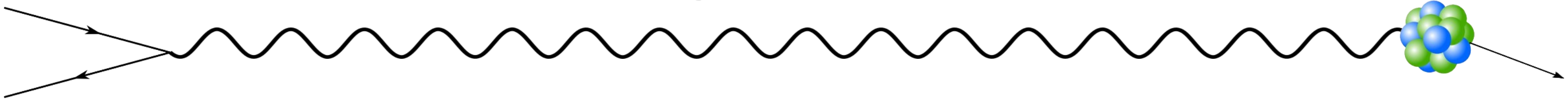
CEνNS Analysis – Region of Interest (ROI)



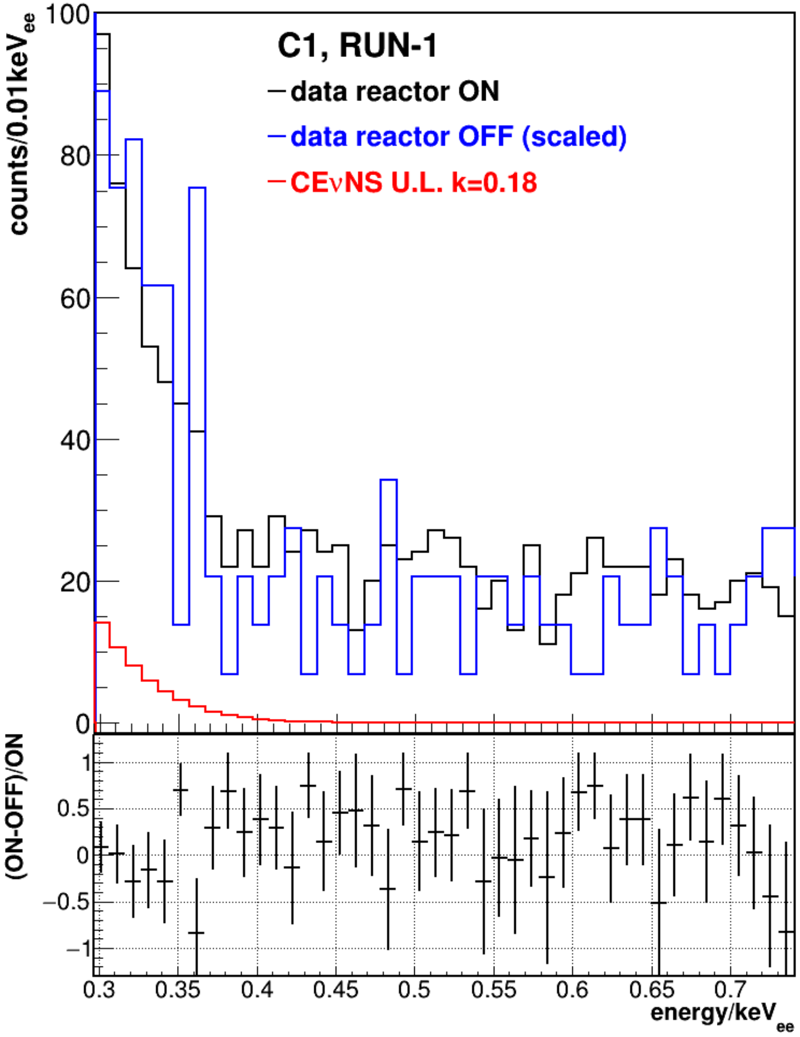
- Criteria:
  - ratio of electronic noise to background MC < 4
- Electronic noise described with an exponential



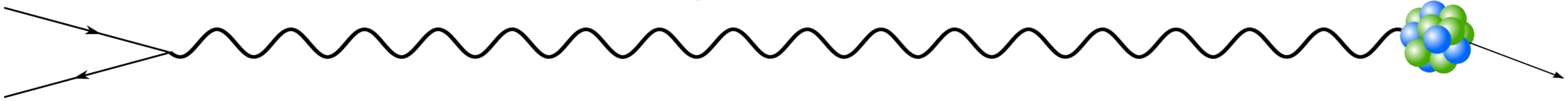
CEνNS Analysis – Data Analysis Strategy



- Simultaneous likelihood fit for all detectors & runs (reactor ON&OFF):
  - theoretical CEνNS signal prediction
  - reactor spectrum
  - MC + exponential electronic noise fit for background description
  - systematic uncertainties



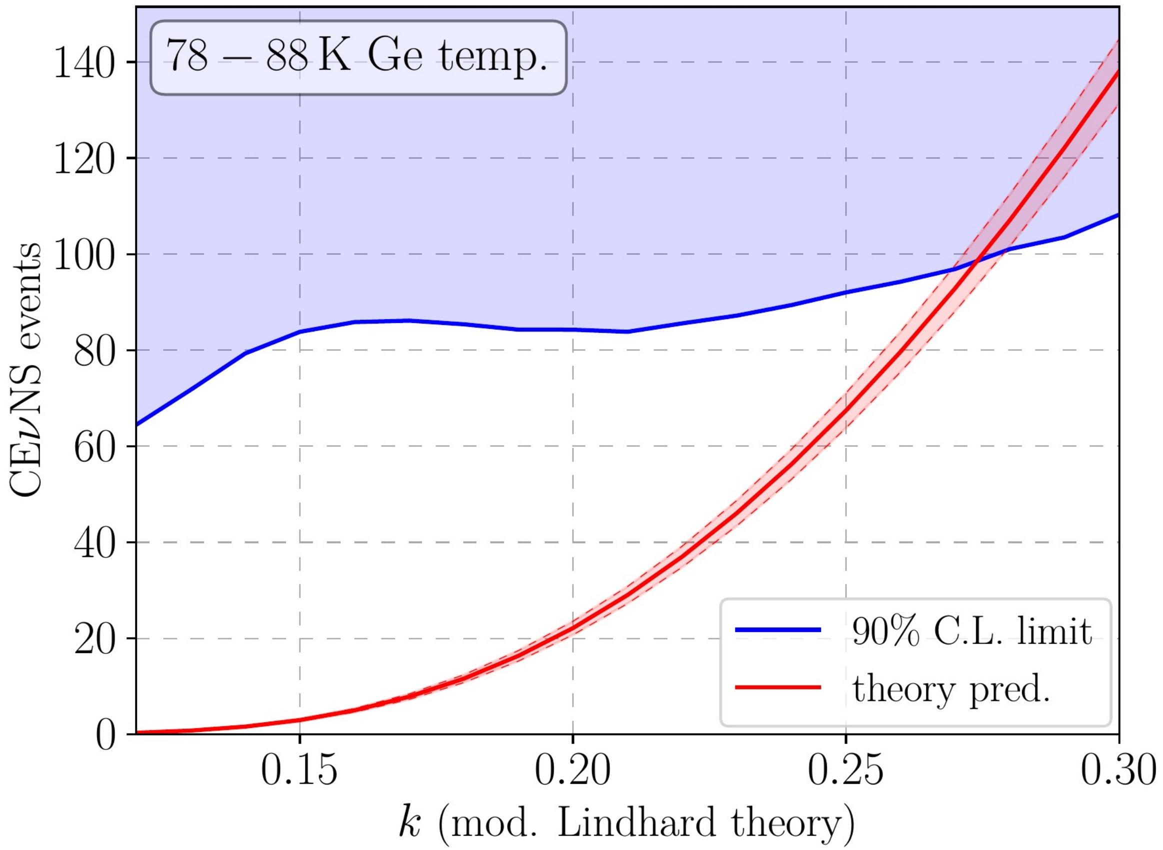
CEνNS Analysis – First Results from CONUS



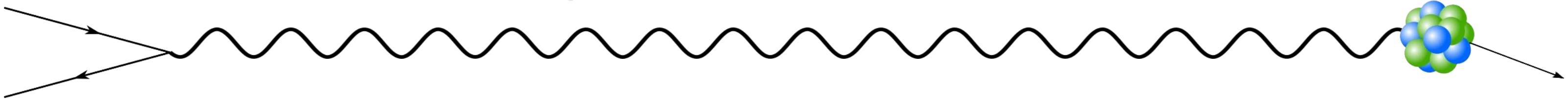
- **Best CEνNS limit at reactor:** < 0.4 d^{-1} kg^{-1} (90 % C.L.)

- Signal expectation depends on quenching factor

➡ For k=0.16: expected CEνNS signal 17x below CONUS upper limit



BSM Analysis – Non-Standard Interactions (NSIs)

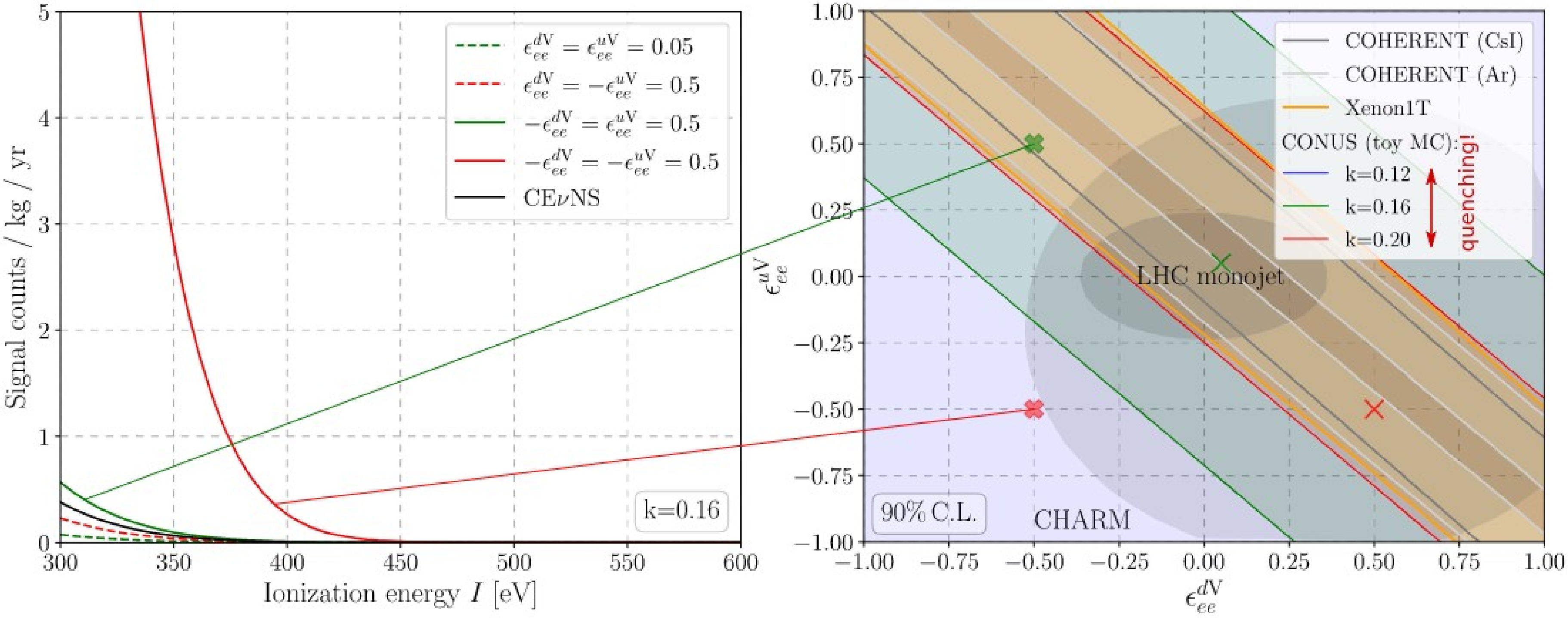


J. High Energ. Phys. 2022, 85 (2022)

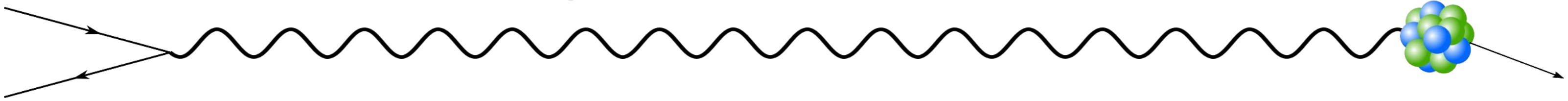
- Non Standard Interactions (NSIs):
  - effective vector/tensor operators

  ➡ new couplings $Q_W \rightarrow Q_{NSI}(\{\epsilon^{q}_{\alpha\beta}\})$

- Vector case: $\left(\frac{d\sigma}{dT_N}\right) = \frac{G_F^2 M}{\pi} {Q^{V}_{NSI}}^2 \left(1 - \frac{MT}{2E_\nu}\right)$



BSM Analysis – Non-Standard Interactions (NSIs)

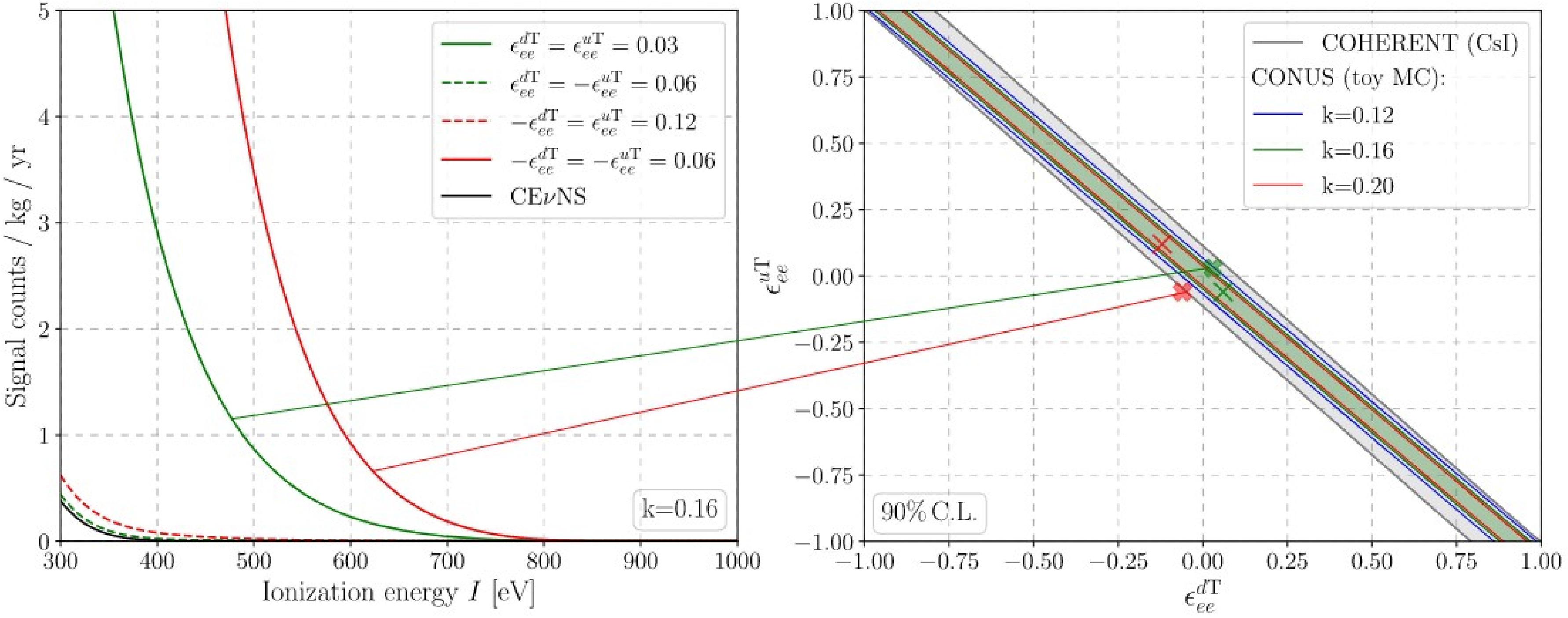


J. High Energ. Phys. 2022, 85 (2022)

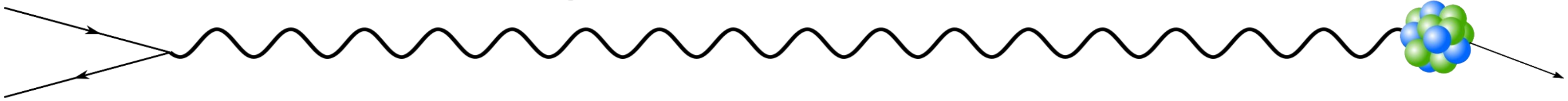
- Non Standard Interactions (NSIs):
  - effective vector/tensor operators

  ➡ new couplings $Q_W \rightarrow Q_{NSI}(\{\epsilon^{q}_{\alpha\beta}\})$

  - Tensor case: $\left(\frac{d\sigma}{dT_N}\right) = \left(\frac{d\sigma}{dT_N}\right)_{CE\nu NS} + \frac{4 G_F^2 M}{\pi} {Q^{T}_{NSI}}^{2} \left(1 - \frac{MT}{4E_\nu^2}\right)$



BSM Analysis – Simplified Models



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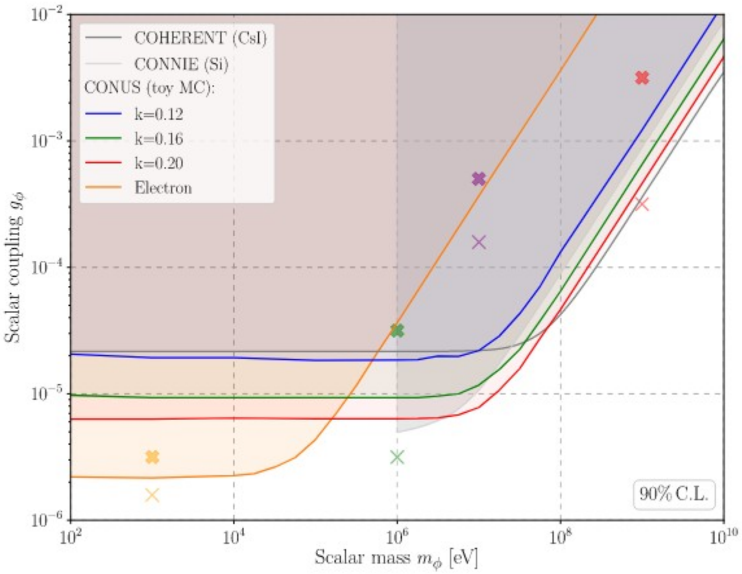
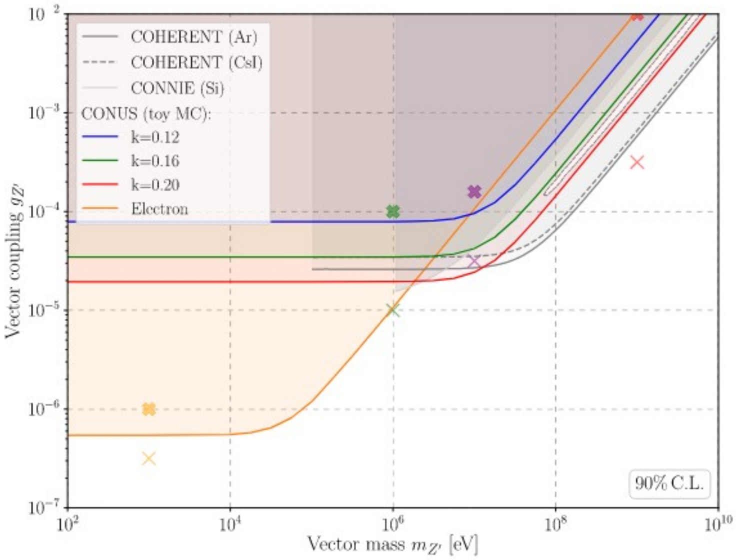
- Simplified models:
  - new light scalar/vector mediators
  - universal couplings
  - light scalar boson ϕ : $\frac{d\sigma_\phi}{dT} = \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$
  - light vector boson Z’: $\frac{d\sigma_{Z'}}{dT} = \left(1 - \frac{3 g_Z^{\nu}{}' g_Z^{q}{}' (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_Z^2{}')}\right)^2 \frac{d\sigma_{SM}}{dT}$

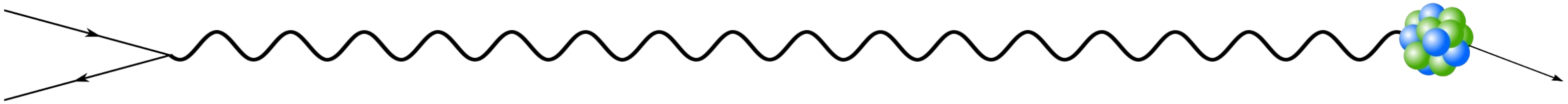
Light scalar boson ϕ



Light vector boson Z’



Analysis of Neutrino Electromagnetic Properies



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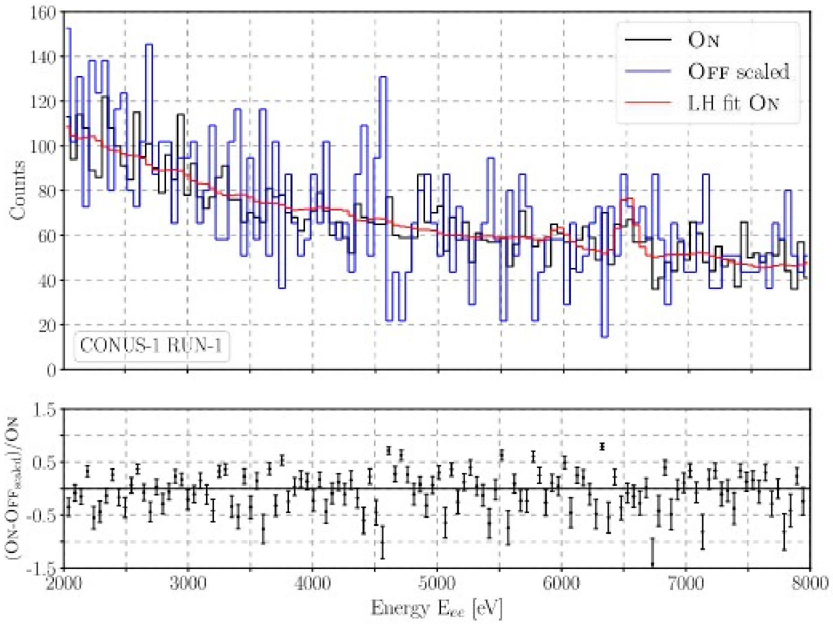
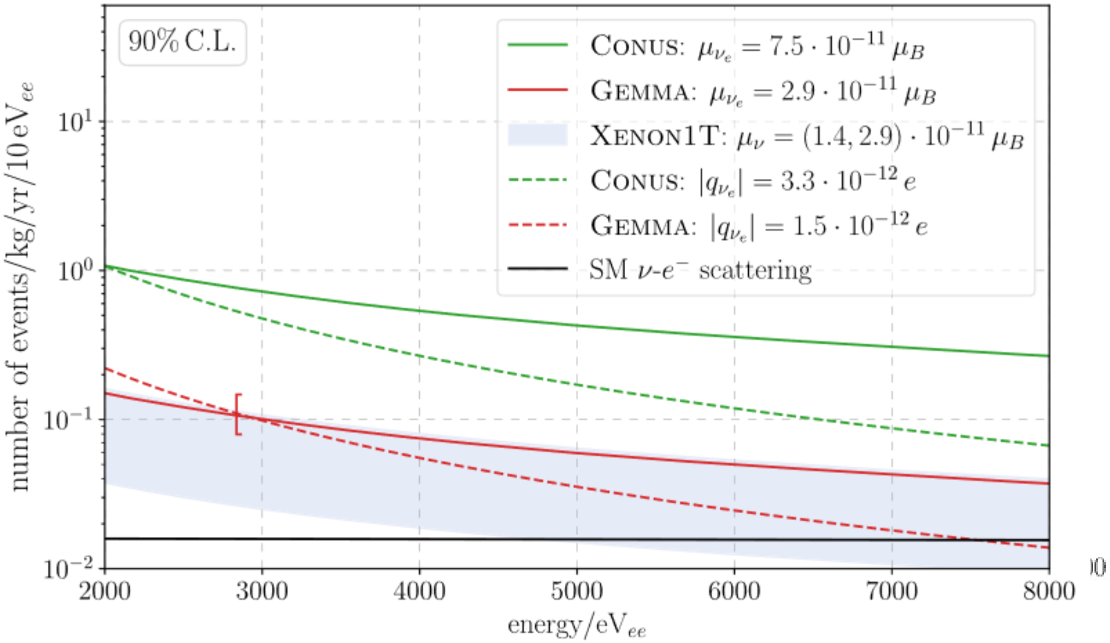
- Neutrino electron scattering channel:

$$\left(\frac{d\sigma}{dT}\right)_{em} = \pi \frac{\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

ROI for NMM Analysis: [2 – 8] keV_{ee}

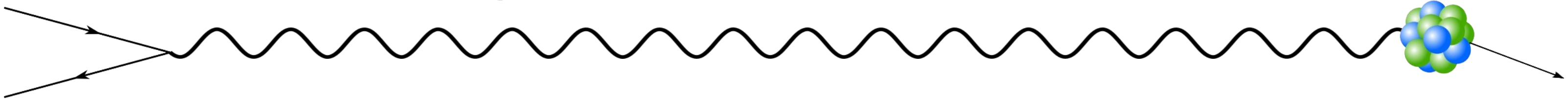




$$\mu_\nu < 7.5 \cdot 10^{-11}\ \mu_B\ (90\%\ C.L.)$$

$$q_\nu < 3.3 \cdot 10^{-12}\ e_0\ (90\%\ C.L.)$$

Summary & Outlook



- CONUS experiment sets best limit on CEνNS with reactor neutrinos
  - detailed description of the Ge detectors given
  - extensive correlated background studies given

Phys. Rev. Lett. 126, 041804 (2021)

Eur. Phys. J. C 81, 267 (2021)

Eur. Phys. J. C 79, 699 (2019)

- Competitive limits for tensor NSIs as well as simplified BSM models

J. High Energ. Phys. 2022, 85 (2022)

- Direct and precise measurement of the ionization quenching factor in germanium down to 0.4 keV_{nr}

Eur. Phys. J. C 82, 815 (2022)

- Future plans:
  - proceeding BSM analyses
  - data taking still ongoing:
    - extended dataset with improved control of environmental parameters + reactor-OFF
  - DAQ upgrade: pulse shape studies for noise, background suppression, lower threshold
  - new experimental site under discussion (reactor off since end of 2021)